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On the market of wind with hydro-pumped storage systems in autonomous Greek islands

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ABSTRACT

In autonomous islands, the wind penetration is restricted due to technical reasons related with the safe operation of the electrical systems. The combined use of wind energy with pumped storage (WPS) is considered as a mean to exploit the abundant wind potential, increase the wind installed capacity and substitute conventional peak supply. In this paper, the experience gained from the analysis of WPS in three specific islands is used towards the estimation of the WPS market in autonomous Greek islands. Parameterized diagrams and a methodology towards the pre-dimensioning and initial design of the WPS are proposed and used towards the estimation of the market in autonomous Greek islands. The objective is to make an initial general prefeasibility study of WPS prospects in the autonomous Greek islands. Results show that there is a significant market for WPS in Greece and the development cost of WPS is competitive to the fuel cost of local power stations in autonomous islands.

Contents

1. Introduction

The autonomous electrical systems in Greek islands are based almost entirely on oil. They are characterized by high wind potential and there is a high investor's interest for wind applications. Given the current infrastructure and the technical constraints, the prospects of wind power to decrease both the system's electricity production cost and the dependence on the oil are limited [1,2]. The reason is that wind farms operating in autonomous systems are subject to output power limitations, related with technical constraints of the conventional generating units, namely the minimum loading levels of the thermal units (technical minimum) and a dynamic penetration limit, applied for stability purposes [1–5].

Investors' applications for large scale wind integration, undertaken also the interconnection of the island with the mainland via an underwater cable, face several objections by local populations. A wind with pumped storage (WPS) system – comprised by new wind farms, two reservoirs for the recycling of water, hydro-turbines, pumps and penstocks – is proposed as a mean to increase the wind installed capacity, substitute expensive fuel oil and reduce the required conventional installed capacity in autonomous islands. Last years, WPS has been analysed by the scientific community for various autonomous islands [6–11].

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In the current paper, the experience gained from the systematic application and thorough analysis of specific case studies [12,13] is used for the creation of parameterized diagrams towards the WPS initial design and estimation of the market, in autonomous Greek islands.

The aim is to make an initially design of WPS in all the autonomous Greek islands. The results show that there is a significant market for WPS in autonomous Greek islands. The cost for the development of WPS is comparable to the operational cost of local power stations in autonomous Greek islands.

2. Methodology

The formulation of parameterized diagrams is based on the results of the thorough analysis of three representative Greek case-studies islands [12,13]. All the analysed case studies and the produced diagrams are based on the following design and operational policy of the WPS [8,12]:

- connection of the wind farms with the pumping station through the central grid,
- peak demand supply of the hydro-turbine,
- consideration of the hydro-turbine as a spinning reserve to increase the direct wind power absorbed,
- double penstock and
- complementary pumping using conventional power given the capacity of the committed conventional units.

The target of parameterization and generalization of the results was an initial prospect of all the former works [1,2,8,12,13] and always various attempts of dimensionless parameterization have been tested.

2.1. Capacity of wind farms, reservoir, hydro-turbine

The required wind capacity is inversely proportional to the wind potential (wind capacity factor) and to the efficiency of the WPS (the ratio of hydro-turbine's energy production to the energy used for pumping), and proportional to the annual mean load and the load factor. The annual mean load introduces the amount of the demand and the load factor the seasonal variations of the demand. The same annual mean load could be appeared in a power with relatively low variations (high load factor) and in another with large variations (low load factor). In the latter case, lower wind capacity is required. During the short peak demand period, the WPS could provide the guaranteed power thanks to the reservoir's stored energy, while the rest period of low demand lower wind capacity is adequate.

Respectively, the required volume of the reservoir is inversely proportional to the available hydraulic head and proportional to the average efficiency of the pumping station.

Then, the wind capacity index δ_W and the reservoir's capacity index δ_R are defined:

$$\delta_W = \frac{P_{W,h,R} \cdot CF_{W,th} \cdot n_{PSU}}{\overline{P_L} \cdot LF} \tag{1}$$

$$\delta_R = \frac{V_{RESERVOIR} \cdot H}{3600 \cdot 102 \cdot P_{W,h,R} \cdot CF_{W,th} \cdot n_P} \tag{2}$$

where $P_{W,h,R}$ is the wind installed capacity in the WPS (MW), $CF_{W,th}$ is the wind capacity factor which introduces the wind potential in the island (%), n_{PSU} is the efficiency of the WPS (%), $\overline{P_L}$ is the annual mean load (MW), LF is the load factor of the island (%), $V_{RESERVOIR}$ is the capacity of the reservoir (m^3), H is the hydraulic head (m), n_P is the efficiency of the pumping station (%).

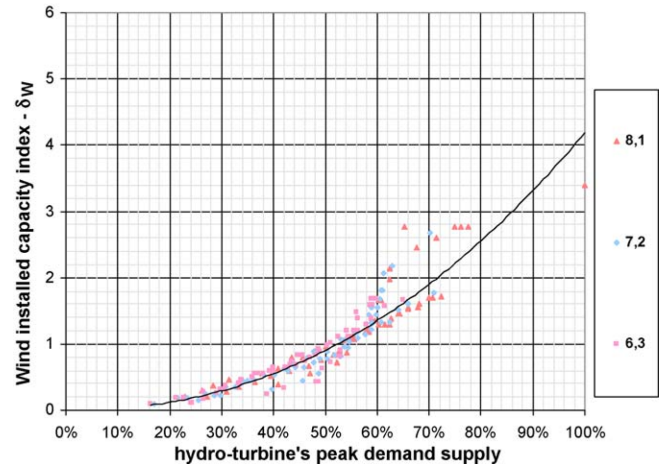

Fig. 1. Diagram for the definition of the WPS wind capacity.

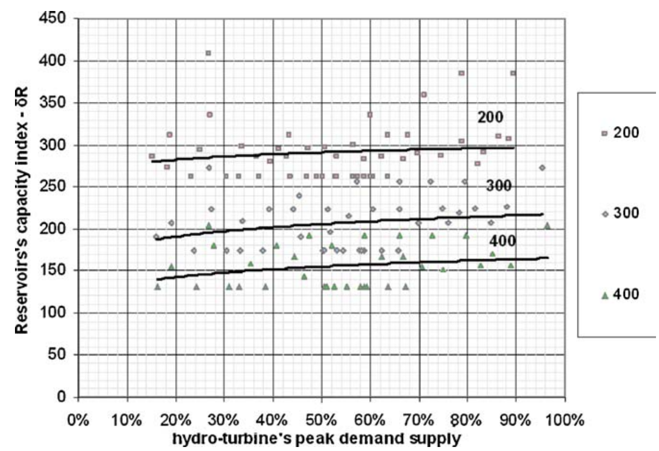

Fig. 2. Diagram for the definition of the WPS reservoir.

The above defined indexes, has been calculated for all the examined case studies and are presented in diagrams (Figs. 1 and 2) as a function of the hydro-turbine's peak demand supply α.

The diagram for the dimensioning of the reservoir is parameterized by the hydraulic head. Then three curves have been adjusted to the available points:

$$\delta_R = \begin{cases} 298.17 \cdot a^{0.0341}, & \gamma\iota\alpha H = 200\,\mathrm{m} \\ 217.74 \cdot a^{0.082}, & \gamma\iota\alpha H = 300\,\mathrm{m} \\ 165.54 \cdot a^{0.0933}, & \gamma\iota\alpha H = 400\,\mathrm{m} \end{cases} \tag{3}$$

$$\delta_W = 4.1889 \cdot a^{2.2133} \tag{4}$$

These diagrams (Figs. 1 and 2) or the formulas (3) and (4) can be used for the initial design and dimensioning of the WPS, given the basic data of the autonomous power system (annual peak demand, mean annual load of the system and the load factor).

To start with the setout of the dimensioning, one of the following parameters should be initially defined:

- the desirable hydro-turbines peak demand supply,
- the available reservoirs capacity,
- or the wind capacity to be installed.

2.2. Energy contribution of the WPS

Wind potential and hydraulic head are site-dependent features, which strongly affects the attractiveness and the profitability of

Table 1
Overview of the formulas and assumptions for the WPS cost estimation.

Equipment—cost symbol	Data/formula for cost estimation (€)
Wind farms (C_W)	1000/kW [17]
Pumps (C_P)	$C_P = N_P \cdot C_{0,P} \cdot \left(\frac{P_{P,rated}}{H_P^{0.3}}\right)^{0.82}$, $C_{0,P} = 1814$
Hydro-turbine (C_T)	$C_T = C_{0,T} \cdot \left(\frac{P_{T,rated}}{H_T^{0.3}}\right)^{0.82}$, $C_{0,T} = 4687$
Reservoir (C_R)	$C_R = 420 \cdot V^{0,7}$
Penstock ($C_{Penstock}$)	$1.25 \cdot \sum_I \left\{ \left[\underbrace{(W_M \cdot \pi D_I \cdot e_I \cdot L) \cdot C_M}_{\text{Material cost}} + \underbrace{(\pi\pi_I \cdot L) \cdot C_I}_{\text{Insulation cost}} + \underbrace{\left(1.5 \cdot \frac{\pi D_I^2}{4} \cdot L\right) \cdot C_E}_{\text{Excavation cost}} \right] \right\}$
Grid connection (C_{GC})	4%*($C_P + C_T + C_R + C_{Penstock}$)
Control system (C_{CS})	1.6%*($C_P + C_T + C_R + C_{Penstock}$)
Transportation of equipment (C_T)	2.4%*($C_P + C_T + C_R + C_{Penstock}$)
Personal (C_P)	30%*($C_P + C_T + C_R + C_{Penstock}$)
Others (C_O)	2%*($C_P + C_T + C_R + C_{Penstock}$)
Operation and maintenance (OMC_{WPS})	2%*($C_P + C_T + C_R + C_{Penstock} + C_W$)

the investment, but does not affect the WPS energy contribution. For the achievement of a desirable WPS energy contribution or turbine's peak demand supply a specific wind energy amount combined with a specific storage capacity are required. The specific wind energy amount can be provided by lower wind installed capacity in a site with higher wind potential, or more wind installed capacity may be required in lower wind potential. Respectively, the energy storage capacity of the reservoir is defined by both the reservoir's water capacity and the available hydraulic head. Then in Fig. 3, although results derived from several case studies with various annual mean wind speed (6.3, 7.2 and 8.1 m/s), and various hydraulic heads (200, 300 and 400 m), the correlation between energy contribution and turbine's peak supply is not affected.[1]

Then, the correlation between energy contribution and hydro-turbine's peak demand supply is described by Fig. 3 or the adjusted formula:

$$\varepsilon_{WPS} = -0.1868 \cdot \alpha^2 + 1.2702 \cdot \alpha - 0.1537 \tag{5}$$

2.3. How the methodology is applied

2.3.1. 1st route: if the peak supply target is defined

If the peak supply target of the WPS is given then:

- 1st step: The wind installed capacity index is derived from Fig. 1.
- 2nd step: The wind installed capacity is calculated by solving formula (1):

$$P_{W,h,R} = \frac{\delta_W \cdot \overline{P_L} \cdot LF}{CF_{W,th} \cdot n_{PSU}} \tag{6}$$

- 3rd step: The reservoirs's capacity index is derived from Fig. 2, given the available hydraulic head H.
- 4th step: The reservoir's capacity is calculated by solving formula (2):

$$V_{RESERVOIR} = \frac{\delta_R \cdot 3600 \cdot 102 \cdot P_{W,h,R} \cdot CF_{W,th} \cdot n_P}{H} \tag{7}$$

[1] The points' dispersion is rather affected by the load factor of the power system and the correlation between wind and demand. Local summer north winds in Aegean sea called "Meltemi", permits a higher hydro-turbine's peak demand supply for specific wind capacity and reservoir and specific energy contribution. During the short peak demand period, thanks to the correlation between wind and demand, WPS could provide more guaranteed power. During the whole year, even with lower wind potential, wind capacity is adequate for the medium loads. With other words, for specific wind capacity and reservoir, a bigger hydro-turbine is justified and higher peak demand can be supplied.

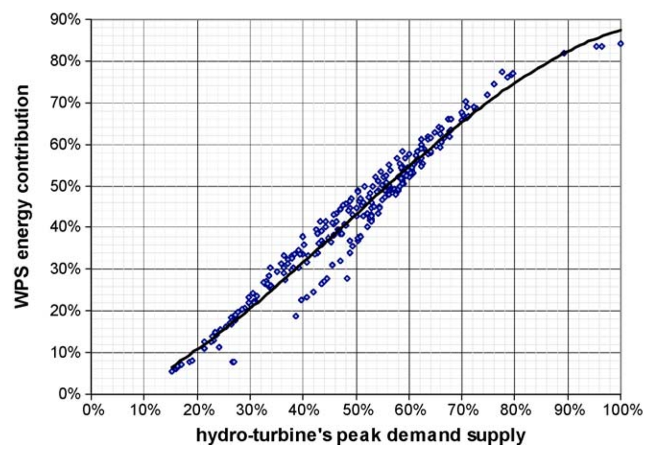

Fig. 3. WPS energy contribution.

2.3.2. 2nd route: if the wind installed capacity is defined

If the wind capacity $P_{W,R}$ to be installed is defined, as it may happen sometimes due to restrictions imposed by the land use or by the land-planning national development plans for RES [14] then:

- 1st step: The wind installed capacity index is calculated by formula (1).
- 2nd step: Then the hydro-turbine's peak demand supply is derived from Fig. 1.
- 3rd step: The reservoir's capacity index is derived from Fig. 2, given the available hydraulic head H.
- 4th step: The required reservoir's capacity is derived from formula (7).

2.3.3. If the reservoir's capacity is defined

If the reservoir's capacity V_R is defined, as it may happen due to site topography restrictions or due to the existing lower reservoir [15], for the calculation of the rest components an iterative procedure is required, as soon as reservoir's capacity index is a function of wind installed capacity. Then:

- 1st step: An initial hypothesis for the hydro-turbine's peak demand supply is used to calculate the wind capacity index from Fig. 1.
- 2nd step: The wind installed capacity is calculated by formula (6).
- 3rd step: The reservoir's capacity index is calculated by formula (3).

- 4th step: The hydro-turbine's peak demand supply is derived from Fig. 2.

The procedure is iterated until the hydro-turbine's peak demand supply converges.

3. Application and results in autonomous Greek islands

The above described methodology, the proposed diagrams and formulas, and Table 1 which provide a route for the WPS cost estimation are applied for all the Greek autonomous systems. Initial WPS design and cost estimations are realized for three levels of hydro-turbine's peak demand supply (30%, 50% and 70%). A mean wind speed 8.1 m/s and hydraulic head $H = 300$ m are used as reference values for all the islands of application.

In the three first columns of Tables 2–4 the basic islands' energy features (peak demand, annual mean load and load factor) are presented. The main components of the WPS (wind installed capacity, hydro-turbine's rated power, penstocks diameters and reservoirs' capacity), the total investment cost of the WPS and the levelized cost in € per kW (kW of cumulative installed capacity and kW of guaranteed capacity) are calculated and results are presented (Tables 2–4).

The calculation procedure is described hereafter:

- Wind installed capacity index δ_W and reservoir's capacity index δ_R are calculated by formulas (3) and (4), given the desirable level of penetration—hydro-turbine's peak demand supply α (30%, 50% and 70%).
- Then, required wind installed capacity $P_{W,h,R}$ and reservoir's capacity $V_{RESERVOIR}$ are calculated by formulas (6) and (7), given the basic energy features (peak demand, annual mean load and load factor) of each island.
- WPS energy contribution is derived by Fig. 3.
- Hydro-turbine's rated power is calculated from the peak demand of each island and the desirable hydro-turbine's peak demand supply α.
- Penstocks' diameter is calculated by empirical formulas for the maximum volume of the pumping and hydro-station [12,16].
- Finally, the cost is estimated by the formulas presented in Table 1 [12].

The cumulative results for the total of autonomous Greek islands show that:

- For 30% hydro-turbine's peak demand supply (hydro-turbines 356 MW) wind installed capacity 374 MW and reservoirs of the order of 27 million m^3 are required. The cumulative investment cost is estimated to 927 million € and the expected energy contribution is 21%.
- For 50% hydro-turbine's peak demand supply (hydro-turbines 593 MW) wind installed capacity 1158 MW and reservoirs of the order of 89 million m^3 are required. The cumulative investment cost is estimated to 2297 million € and the expected energy contribution is 43%.
- Finally, for 70% hydro-turbine's peak demand supply (hydro-turbines 831 MW), wind installed capacity 2438 MW and reservoirs of the order of 192 million m^3 are required. The cumulative investment cost is estimated to 4309 million € and the expected energy contribution is 64%.

Today, Greek islands are based almost entirely on oil. For comparison, the cumulative annual fuel cost in Greek autonomous islands is estimated to 670 million € (for price for Brent 54$/b), while the installation cost of conventional units is estimated to

Table 2
Initial estimation of WPS in Greek islands aiming at hydro-turbine's peak demand supply 30% and 21% energy contribution ($H = 300$ m, annual mean speed 8.1 m/s).

Island	Peak demand (MW)	Annual mean load (MW)	Load factor	Wins capacity (MW)	Hydro-turbine rated power (MW)	Pump's penstock diameter (m)	Turbine's penstock diameter (m)	Reservoir's capacity ($10^6 m^3$)	Autonomy (turbine's rated power operation) (h)	Wind turbine's cost (εκ €)	Pumped storage and hydro-station cost (εκ €)	Total WPS investment cost (εκ €)	€/kW (wind and hydro-turbine capacity)	€/kW (hydro-turbine capacity)
Crete	605	323	53%	227	181	4.2	6.7	17	67	227	150	437	1070	2407
Rodos	170	80.6	47%	48	51	1.9	3.6	3.5	50	48	52	120	1218	2354
Kalimnos-Kos	66.4	28.8	43%	16	19.9	1.1	2.2	1.2	44	16	25	51	1415	2577
Lesvos	59.5	28.1	47%	19	17.9	1.2	2.1	1.4	58	19	27	56	1524	3157
Paros	56.0	20.5	37%	10	16.8	0.9	2.1	0.7	32	10	19	36	1357	2155
Chios	43.4	20.9	48%	14	13.0	1.0	1.8	1.0	56	14	21	43	1617	3307
Samos	34.0	15.2	45%	9	10.2	0.9	1.6	0.7	50	9	17	33	1668	3209
Santorini	32.7	11.4	35%	5	9.8	0.6	1.6	0.38	29	5	12	23	1498	2296
Myconos	31.4	11.0	35%	5	9.4	0.6	1.5	0.37	29	5	12	22	1515	2328
Syros	21.1	11.2	53%	7	6.3	0.7	1.3	0.52	60	7	13	26	1909	4046
Lemnos	14.2	6.65	47%	4	4.3	0.55	1.0	0.29	50	4	9	17	2036	3911
Milos	9.66	3.87	40%	2	2.9	0.39	0.85	0.15	38	2	6	11	2146	3647
Karpathos-Kasos	7.88	3.29	42%	2	2.4	0.36	0.77	0.13	39	2	5	9	2279	3944
Ikaria	7.55	2.75	36%	1	2.3	0.33	0.75	0.10	34	1	5	8	2248	3663
Sifnos	5.53	1.74	31%	0.7	1.7	0.23	0.65	0.052	23	1	3	5	2283	3267
Patmos	4.60	1.69	37%	0.8	1.4	0.24	0.59	0.06	31	1	3	5	2532	3966
Skyros	3.98	1.66	42%	0.9	1.2	0.27	0.55	0.07	43	1	4	6	2775	4975
Kythnos	3.00	0.84	28%	0.3	0.9	0.15	0.48	0.022	18	0.3	2.0	3	2600	3455
Serifos	2.98	0.83	28%	0.3	0.9	0.15	0.47	0.022	18	0.3	2.0	3	2608	3471
Amorgos	2.83	1.00	35%	0.4	0.8	0.18	0.46	0.032	28	0.4	2.3	4	2872	4344
Simi	2.70	1.32	49%	0.8	0.8	0.25	0.45	0.06	52	1	3	5	3160	6222
Astipalaia	1.80	0.66	37%	0.3	0.54	0.14	0.37	0.019	27	0.3	1.7	3	3275	4885
Megisti	0.56	0.24	42%	0.1	0.17	0.10	0.21	0.010	43	0.1	1.0	2	5010	9009
Total	1187	577	49%	374	356			27		374	395	927		

Table 3
Initial estimation of WPS in Greek islands aiming at hydro-turbine's peak demand supply 50% and 43% energy contribution (H = 300m, annual mean speed 8.1 m/s).

Island	Peak demand (MW)	Annual mean load (MW)	Load factor	Wins capacity (MW)	Hydro-turbine rated power (MW)	Pump's penstock diameter (m)	Turbine's penstock diameter (m)	Reservoir's capacity (10^6 m^3)	Autonomy (turbine's rated power operation)	Wind turbine's cost (εκ €)	Pumped storage and hydro-station cost (εκ €)	Total WPS investment cost (εκ €)	€/kW (wind and hydro-turbine capacity)	€/kW (hydro-turbine capacity)
Crete	605	323	53%	702	302	7.3	8.7	54	131	702	316	1145	1139	3785
Rodos	170	80.6	47%	147	85	3.4	4.6	11.3	98	147	107	297	1279	3496
Kalimnos-Kos	66.4	28.8	43%	51	33.2	2.0	2.9	3.9	86	51	51	122	1456	3678
Lesvos	59.5	28.1	47%	59	29.8	2.1	2.7	4.5	112	59	55	136	1532	4584
Paros	56.0	20.5	37%	31	28.0	1.5	2.7	2.3	62	31	38	83	1420	2971
Chios	43.4	20.9	48%	42	21.7	1.8	2.3	3.2	109	42	43	103	1613	4744
Samos	34.0	15.2	45%	29	17.0	1.5	2.1	2.2	97	29	34	77	1665	4524
Santorini	32.7	11.4	35%	16	16.4	1.1	2.0	1.24	56	16	24	50	1548	3082
Myconos	31.4	11.0	35%	16	15.7	1.1	2.0	1.20	56	16	24	49	1563	3122
Syros	21.1	11.2	53%	22	10.6	1.3	1.6	1.68	117	22	27	60	1851	5700
Lemnos	14.2	6.65	47%	12	7.1	0.97	1.3	0.93	96	12	18	38	1976	5358
Milos	9.66	3.87	40%	6	4.8	0.69	1.10	0.48	73	6	12	23	2095	4821
Karpathos-Kasos	7.88	3.29	42%	5	3.9	0.64	0.99	0.41	76	5	11	20	2205	5199
Ikaria	7.55	2.75	36%	4	3.8	0.58	0.97	0.34	66	4	10	18	2193	4758
Sifnos	5.53	1.74	31%	2.2	2.8	0.41	0.83	0.170	45	2	6	11	2251	4054
Patmos	4.60	1.69	37%	2.4	2.3	0.43	0.76	0.19	59	2	7	12	2447	5020
Skyros	3.98	1.66	42%	2.9	2.0	0.47	0.71	0.22	83	3	7	13	2611	6459
Kythnos	3.00	0.84	28%	0.9	1.5	0.27	0.61	0.070	34	0.9	3.7	6	2541	4094
Serifos	2.98	0.83	28%	0.9	1.5	0.27	0.61	0.070	35	0.9	3.7	6	2548	4114
Amorgos	2.83	1.00	35%	1.3	1.4	0.32	0.60	0.103	54	1.3	4.5	8	2747	5365
Simi	2.70	1.32	49%	2.4	1.4	0.43	0.58	0.19	101	2	6	11	2896	8112
Astipalaia	1.80	0.66	37%	0.8	0.90	0.25	0.48	0.063	51	0.8	3.2	5	3096	5922
Megisti	0.56	0.24	42%	0.4	0.28	0.18	0.27	0.032	83	0.4	1.9	3	4430	11000
Total	1187	577	49%	1158	593			89		1158	814	2297		

Table 4
Initial estimation of WPS in Greek islands aiming at hydro-turbine's peak demand supply 70% and 64% energy contribution (H = 300m, annual mean speed 8.1 m/s).

Island	Peak demand (MW)	Annual mean load (MW)	Load factor	Wins capacity (MW)	Hydro-turbine rated power (MW)	Pump's penstock diameter (m)	Turbine's penstock diameter (m)	Reservoir's capacity (10^6 m^3)	Autonomy (turbine's rated power operation)	Wind turbine's cost (εκ €)	Pumped storage and hydro-station cost (εκ €)	Total WPS investment cost (εκ €)	€/kW (wind and hydro-turbine capacity)	€/kW (hydro-turbine capacity)
Crete	605	323	53%	1479	423	10.7	10.3	116	202	1479	525	2214	1164	5228
Rodos	170	80.6	47%	310	119	4.9	5.5	24.4	151	310	176	557	1296	4677
Kalimnos-Kos	66.4	28.8	43%	107	46.5	2.9	3.4	8.4	133	107	83	223	1458	4807
Lesvos	59.5	28.1	47%	125	41.7	3.1	3.2	9.8	173	125	91	252	1513	6044
Paros	56.0	20.5	37%	64	39.2	2.2	3.1	5.1	95	64	61	149	1441	3810
Chios	43.4	20.9	48%	89	30.4	2.6	2.8	7.0	169	89	71	189	1584	6210
Samos	34.0	15.2	45%	61	23.8	2.2	2.4	4.8	149	61	56	140	1636	5864
Santorini	32.7	11.4	35%	34	22.9	1.6	2.4	2.68	86	34	39	89	1562	3888
Myconos	31.4	11.0	35%	33	22.0	1.6	2.3	2.59	87	33	38	87	1575	3937
Syros	21.1	11.2	53%	46	14.8	1.9	1.9	3.63	181	46	45	109	1787	7375
Lemnos	14.2	6.65	47%	26	9.9	1.40	1.6	2.01	149	26	30	68	1908	6819
Milos	9.66	3.87	40%	13	6.8	1.01	1.30	1.04	113	13	20	41	2033	6010
Karpathos-Kasos	7.88	3.29	42%	11	5.5	0.93	1.18	0.89	118	11	17	36	2126	6467
Ikaria	7.55	2.75	36%	9	5.3	0.84	1.15	0.73	102	9	16	31	2127	5870
Sifnos	5.53	1.74	31%	4.7	3.9	0.60	0.99	0.367	70	5	10	19	2208	4869
Patmos	4.60	1.69	37%	5.1	3.2	0.63	0.90	0.40	92	5	10	20	2361	6096
Skyros	3.98	1.66	42%	6.2	2.8	0.69	0.84	0.49	128	6	11	22	2472	7951
Kythnos	3.00	0.84	28%	1.9	2.1	0.39	0.73	0.152	53	1.9	5.8	10	2488	4777
Serifos	2.98	0.83	28%	1.9	2.1	0.38	0.72	0.152	54	1.9	5.8	10	2494	4801
Amorgos	2.83	1.00	35%	2.8	2.0	0.47	0.71	0.224	83	2.8	7.0	13	2635	6414
Simi	2.70	1.32	49%	5.1	1.9	0.63	0.69	0.40	157	5	10	19	2696	9999
Astipalaia	1.80	0.66	37%	1.7	1.26	0.36	0.56	0.136	79	1.7	5.1	9	2948	6997
Megisti	0.56	0.24	42%	0.9	0.39	0.26	0.31	0.069	129	0.9	3.0	5	4027	13013
Total	1187	577	49%	2438	831			192		2438	1336	4309		

1500–2000 million €. As a result, the financial benefit from the fuel and conventional installed capacity substitution may constitute a significant reason for the decision towards the large scale integration of WPS plants in Greek islands.

Very small autonomous islands (Anafi, Ag.Eustratios, Othonoi, Ereikousa, Donousa, Agathonisi and Antikithira) are not considered in this analysis. Very small size of these islands, and the expensive cost of very small WPS systems, indicates that other hybrid solutions (i.e. based on photovoltaics and batteries) may be more convenient and profitable.

4. Conclusions

In this paper general parameterized diagrams and a methodology for the initial design and cost estimation of the WPS has been presented. A methodology has been described and applied in the total of autonomous Greek islands, providing an estimation of the Greek WPS market. The results could be used for the energy decision making in autonomous Greek islands.

The application for the total of autonomous Greek islands, show that the required cost for the development of WPS plants is competitive to the fuel cost of existing local power stations.

For three representative levels of WPS penetration examined (30%, 50% and 70% hydro-turbine's peak demand supply), the energy contribution reaches 21%, 43% and 64%, requires investment cost of 927, 2297 and 4309 million €, while conventional installed capacity of 356, 593 and 831 MW is substituted.

An important advantage of the WPS is that the production cost is to a large extent known in advance, contrary to the current cost which depends strongly on the oil price. Thus the installation of WPS can provide both financial and environmental benefits and is strongly recommended.

The whole procedure is based on thorough analysis of representative case studies and refers to specific design and operational policy. Nevertheless, the whole procedure can be applied for any different case of operation or different assumptions and restrictions. Consequently, the whole approach and the results constitute a significant tool for the islands energy design and maybe for the evaluation of applications for WPS in Greek islands.

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